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Real-world Carbon Abatement Costs of Hybrid and Electric Vehicles in China and India

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International Energy Studies Group

ETA Seminar

January 22, 2015

Team Members and Collaborators

Our Team

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Summary of work and key findings

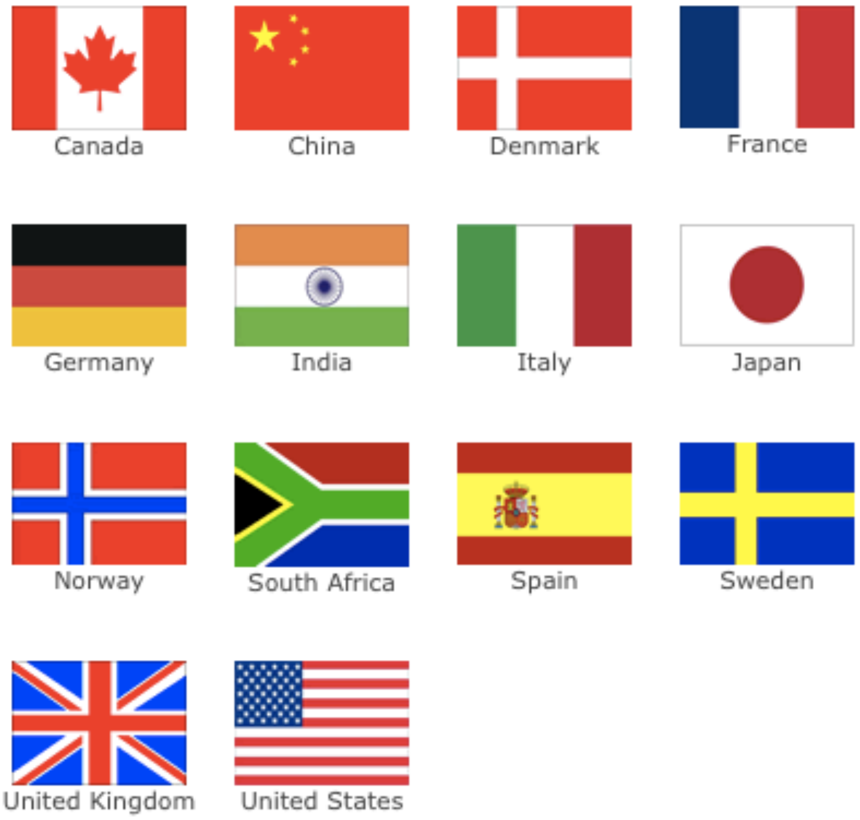
The Existing Consensus: Hybrid and Electric Vehicles (H&EVs) as climate mitigation technologies in China and India are widely dismissed as marginal and expensive. However, there are very few studies of marginal abatement cost of carbon (MACC) for transportation. The few studies that exist do not consider real-world use or appropriate vehicle design.

Our findings: When you consider real-world fuel efficiency and appropriate vehicle design: *In 2030, (1) HEVs are a "no-regret" option in India & very low cost in China, (2) BEVs are a "no-regret" option in India and China, (3) HEVs & BEVs are a lower cost option in China than previous estimates and other measures such as BRT etc and (4) Net carbon savings result from BEVs even if the grid does not become cleaner*

Project Context: Clean Energy Ministerial

Electric Vehicles Initiative (EVI)

Participants



Non-Clean Energy Ministerial Government Participants

LBNL is the lead research partner for EVI

CLEAN ENERGY MINISTERIAL

Accelerating the Transition to Clean Energy Technologies

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News

EVI Research Highlights the Potential for Electric Vehicles in India

EVs could save 4.8 billion barrels of oil, 270 million tons carbon dioxide (CO2)

Tuesday, May 20, 2014

Categories

- CEM News (55)
  - Theme (50)
  - Ministerial Meeting (15)
  - Initiative (48)
  - Public-Private Engagement (4)

Tags

21CPP | Air Conditioners | AMI | analysis | Anna-Karin Hatt | Australia | awards | Bioenergy | biofuels | biomass

Impacts of Transportation in India and China

1. **High congestion and poor public transportation -> Very low average trip speeds**
2. **Very poor safety: annual road accident deaths in India are the highest in the world**
3. Major cause of urban air pollution
4. Major contributor to each country's oil import dependence

Greenhouse Gases (GHGs) are insignificant today (< 10% of energy related GHGs in India and China)

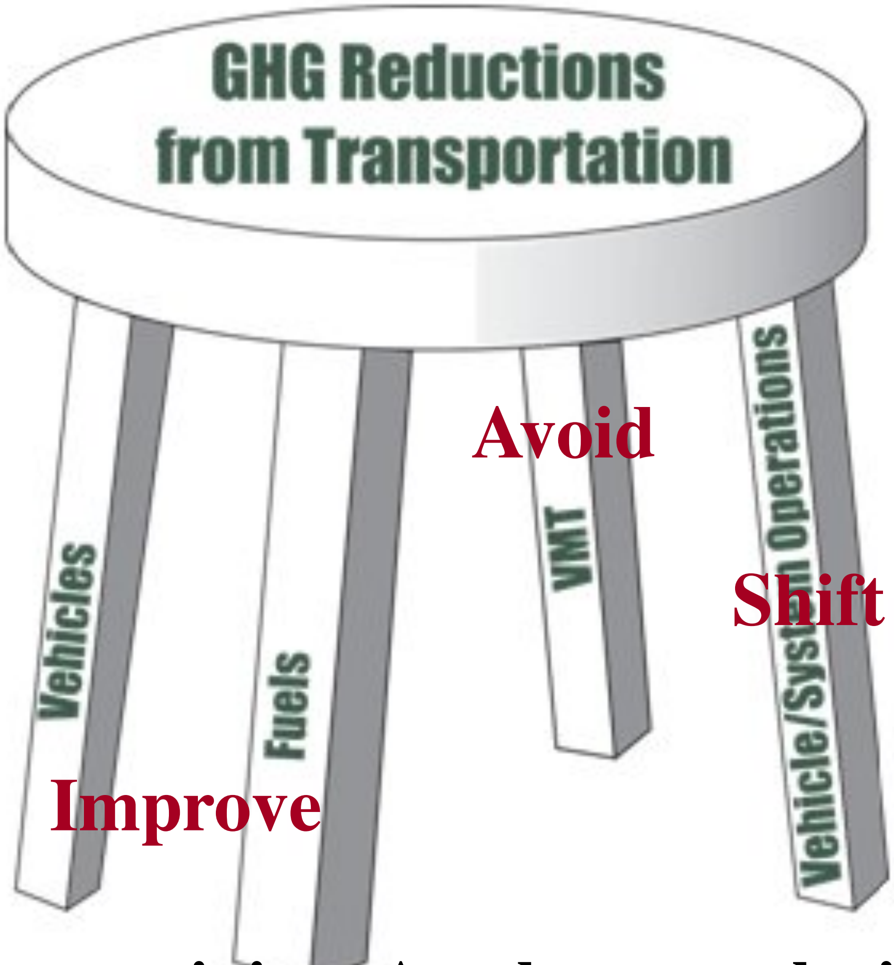
Given this, a consensus has formed regarding the best approach to clean up transportation in both countries

Sustainable Transportation Policy Paradigm (A-S-I)

(A)void increases in demand for travel

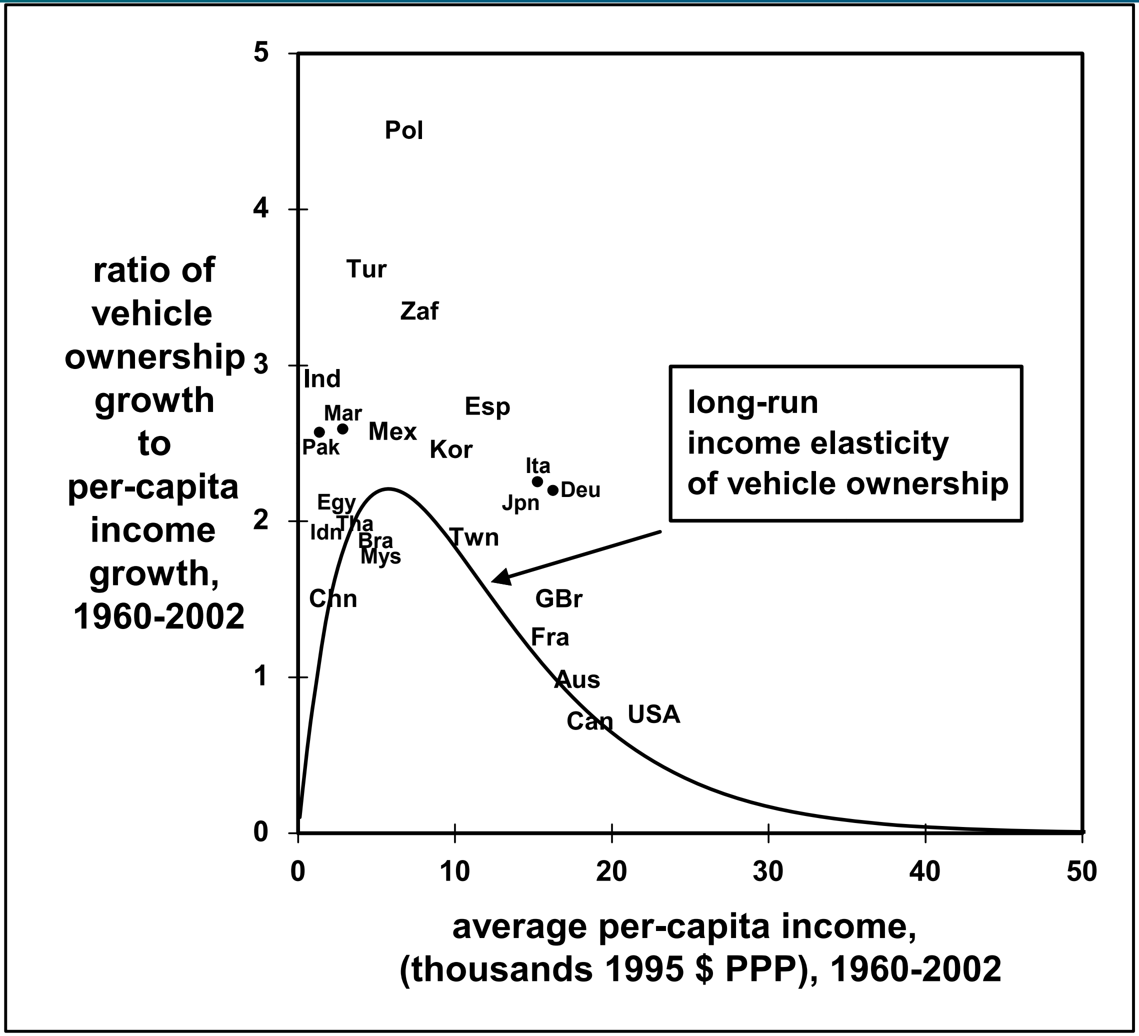
(S)hift travelers to the most efficient modes

(I)mprove vehicle technology (fuel efficiency, alternative fuels, advanced vehicles)



Dominant opinion: An almost exclusive Avoid-Shift focus is optimal for India/ China

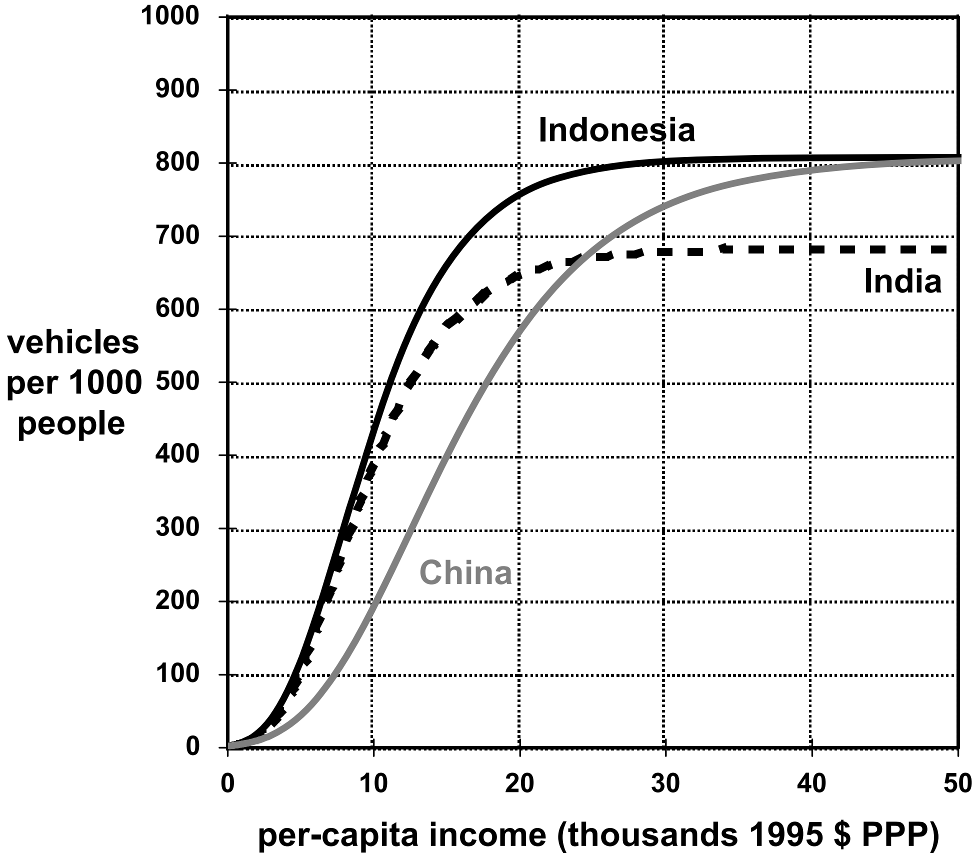
Problems with A-S Focus: The Car-Wealth Nexus



Source: Dargay et al (2007)

Explosive growth begins between $8K-$10K per capita HH income (PPP adj) (Dargay et al 2007)

The Car-Wealth Nexus: Aspirations of the Middle Class



Source: Dargay et al (2007)

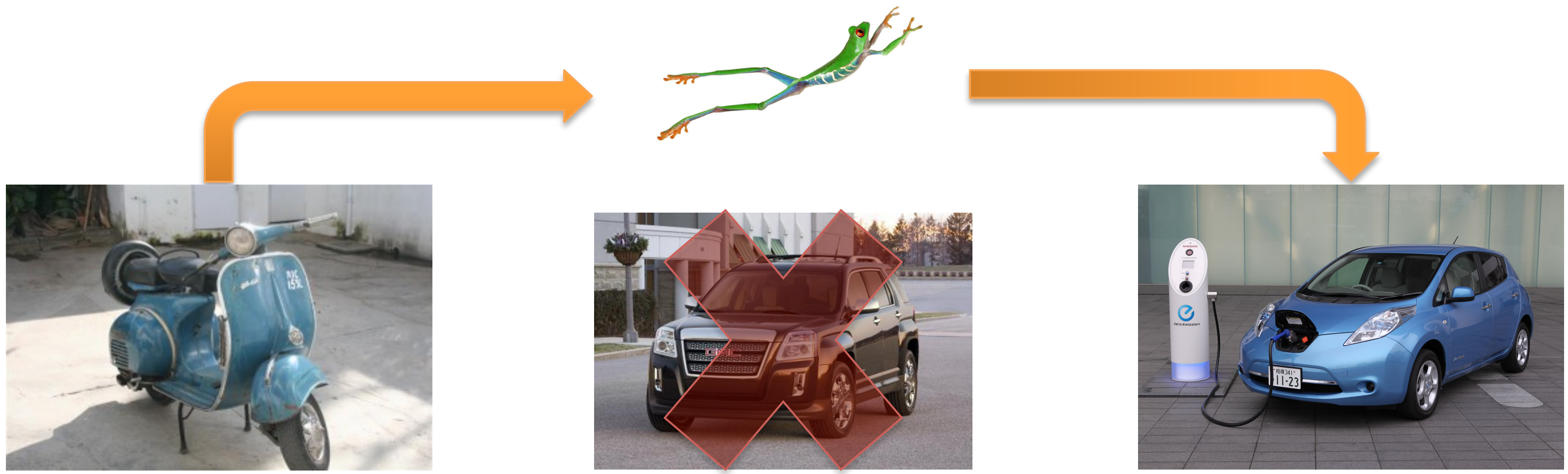
According to these projections, by 2030, Vehicle ownership per 1000 people will be:

China ~ 269 (74)
India ~ 110 (17)
Indonesia ~ 166 (69)

Transportation sector GHG emissions growth rate to 2040 ~ 6% per year for China/India

China and India are still below lift-off HH income levels. China will get there in 2020s, India in early 2030s

The Opportunity? Leapfrogging



- Rapidly growing fleet implies a “no replacements” approach will yield substantial GHG and energy savings
- However, investment in advanced vehicles and alternative fuels must begin today
- **Improving** transportation technologies must be a very important focus in China and India

Carbon Abatement & Costs of Advanced Vehicles

- Our focus: Advanced technology vehicles – hybrid and battery electric vehicles.
  - Fuel efficiency improvements in conventional vehicles are widely known to be very cost-effective with substantial savings potential. Hence we don't focus on this straightforward case.
- The popular metric we model is called the MACC Curve
  - Marginal Abatement Cost of Carbon (MACC) of given technology ($ invested/ton GHGs saved) (y-axis)
  - Carbon abatement potential in 2030 of given technology (x-axis)
  - Goal: Prioritize climate mitigation actions

Method to the MACCness! (y-axis)

$$\frac{(Annualized\ incremental\ manufacturing\ cost\ [\$]) - (Annual\ operating\ cost\ savings\ [\$])}{Annual\ emission\ savings\ (metric\ ton\ CO_2)}$$

- Incremental manufacturing cost (Source: NAS Report)
- Annual operating cost savings = Annual $\text{ICE}_{\text{operating cost}}$ – Annual $\text{HEV}_{\text{operating}}$ cost OR $\text{BEV}_{\text{operating cost}}$
- Annual operating cost for BEV = $\frac{Wh}{km} x \frac{km}{year} x \frac{\$}{kWh} x \frac{kWh}{1000\ Wh}$
- Terms that are time variable in MACC:
    - Numerator: Oil price (we use the **low scenario** from IEA), marginal cost of electricity generation, annual VMT, incremental manufacturing cost, **vehicle fuel economy (Wh/km and L/km)**.
    - Denominator: grid emissions factors, annual VMT, **vehicle fuel economy**.

Method to the MACCness! (x-axis)

Total GHG abatement potential for 2030 for each vehicle technology is calculated as follows:

$$\sum\left(\frac{Conventional\ Vehicle\ CO_2}{km} - \frac{HEV\ or\ BEV\ CO2}{km}\right)\ x\ \frac{km}{year/vehicle}\ x\ HEVs\ or\ BEVs\ in\ use\ in\ that\ year$$

Summed from previous years to target year

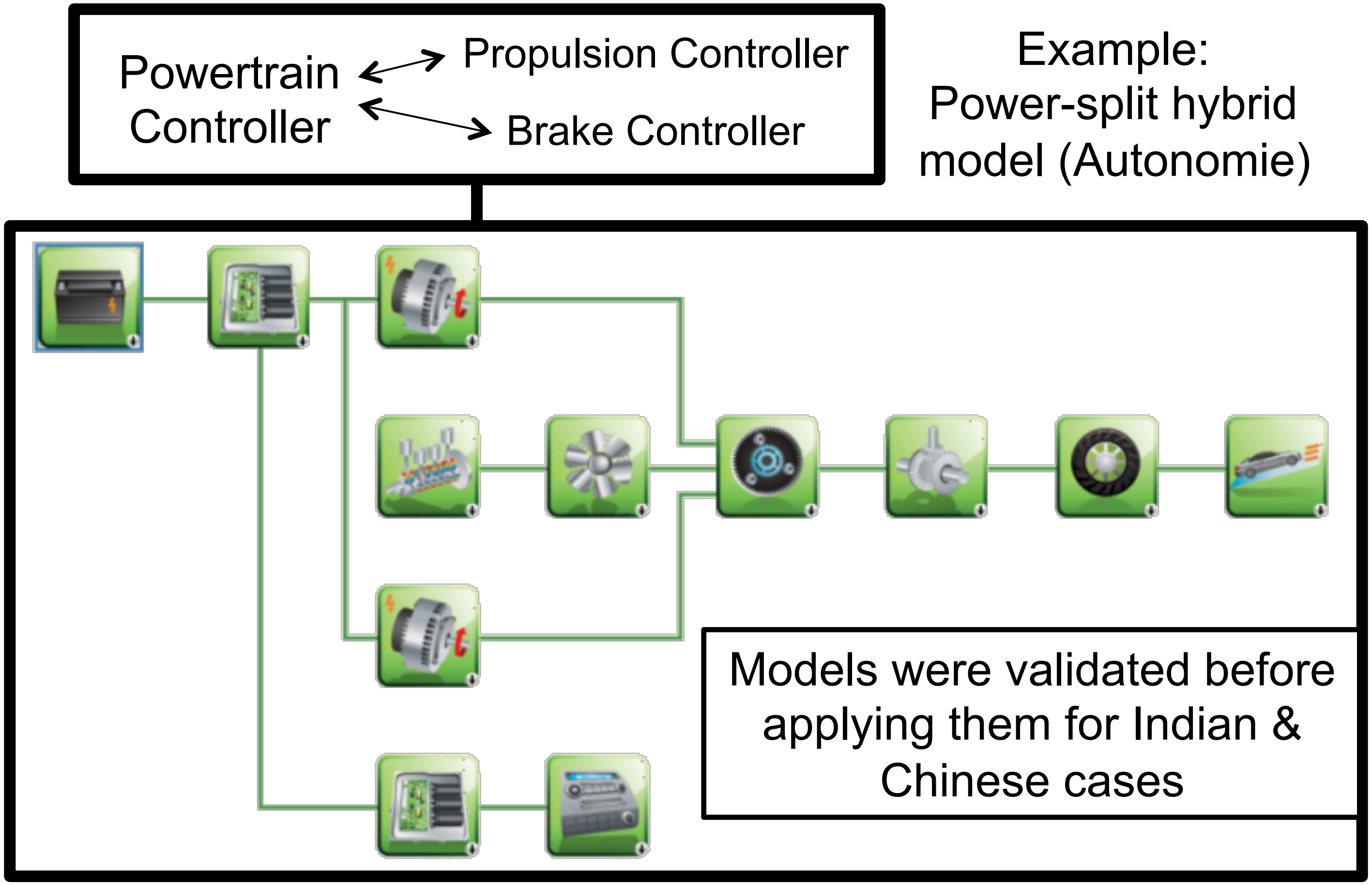
- For HEV and BEV fleet growth rates we use “announced policies” in both India and China
- Many studies calculate abatement potential simply by assuming that a certain share of new sales going forward will be the vehicle technology of interest (BEVs and HEVs)
- Hence, ours is a **definite lower bound abatement potential**

Transportation MACC Literature

- There are very few MACC studies for India and China
  - McKinsey studies for both countries are the original MACC analyses
  - Others are more recent
- Most studies show that hybrid and electric vehicles have a high marginal abatement cost in India and China and fairly limited overall abatement potential
  - They mostly support the stance of Avoid-Shift only proponents
- None of the studies, however, consider real-world fuel efficiency and appropriate battery sizing based on actual travel behavior

Real-World Fuel Efficiency Modeling - Autonomie

Autonomie Simulation for Fuel Economy and GHG emissions -> Marginal Abatement Cost Model

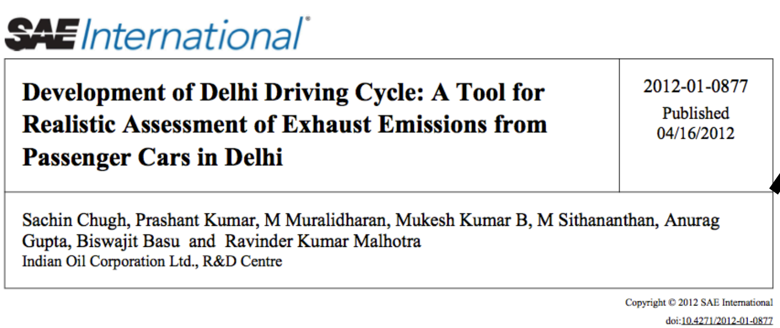


Example:
Power-split hybrid model (Autonomie)

Engineering Results in International Journal of Powertrains and Applied Energy

Real-world Driving Cycle Data

- Used published literature for both countries (3 Indian metropolitan regions and 11 Chinese large cities)
- Used smart phones as speed-time sensors in Indian cities only - primarily as a sanity check



SAE International

Development of Delhi Driving Cycle: A Tool for Realistic Assessment of Exhaust Emissions from Passenger Cars in Delhi

2012-01-0877
Published
04/16/2012

Sachin Chugh, Prashant Kumar, M Muralidharan, Mukesh Kumar B, M Sithananthan, Anurag Gupta, Biswajit Basu and Ravinder Kumar Malhotra
Indian Oil Corporation Ltd., R&D Centre

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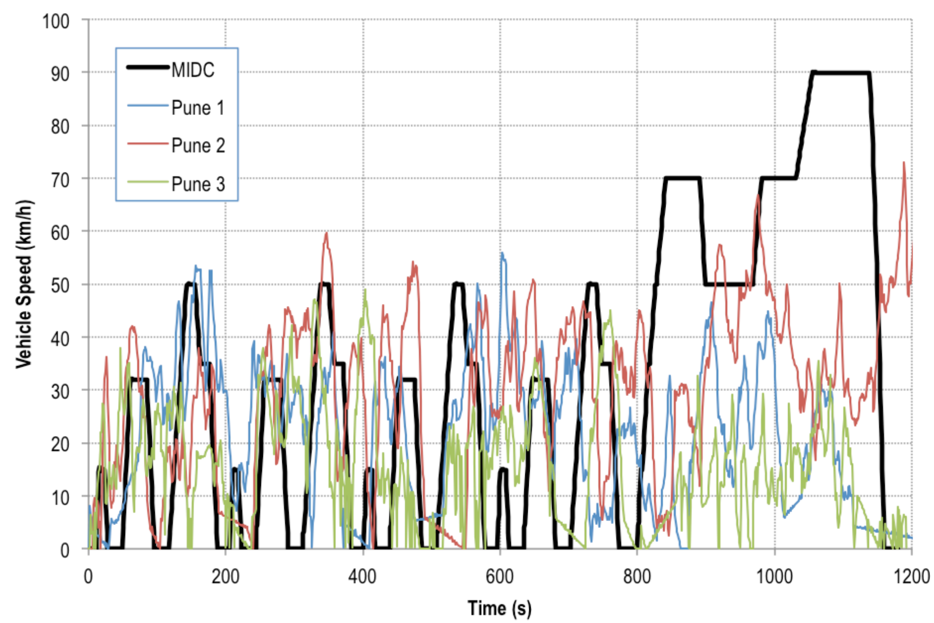
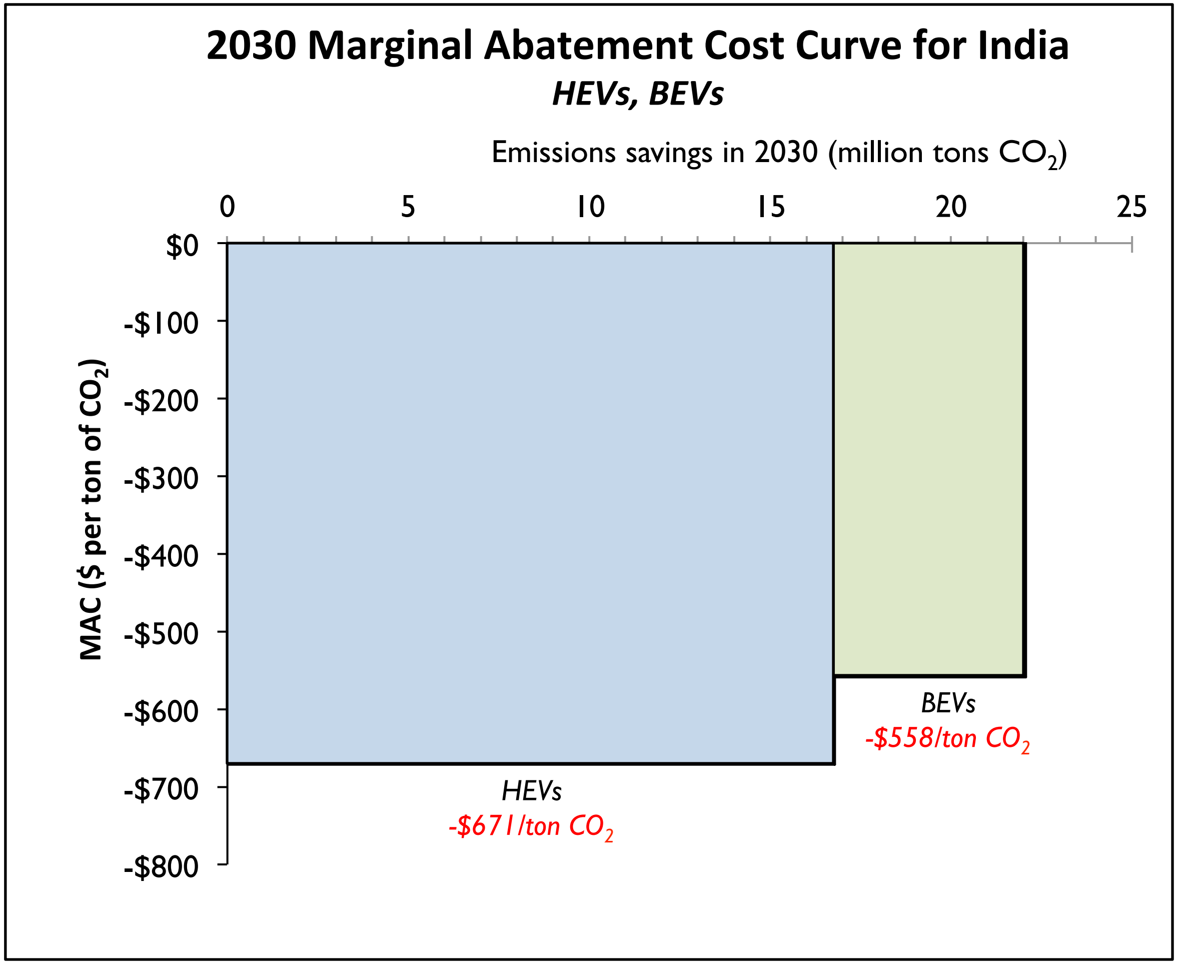
doi:10.4271/2012-01-0877



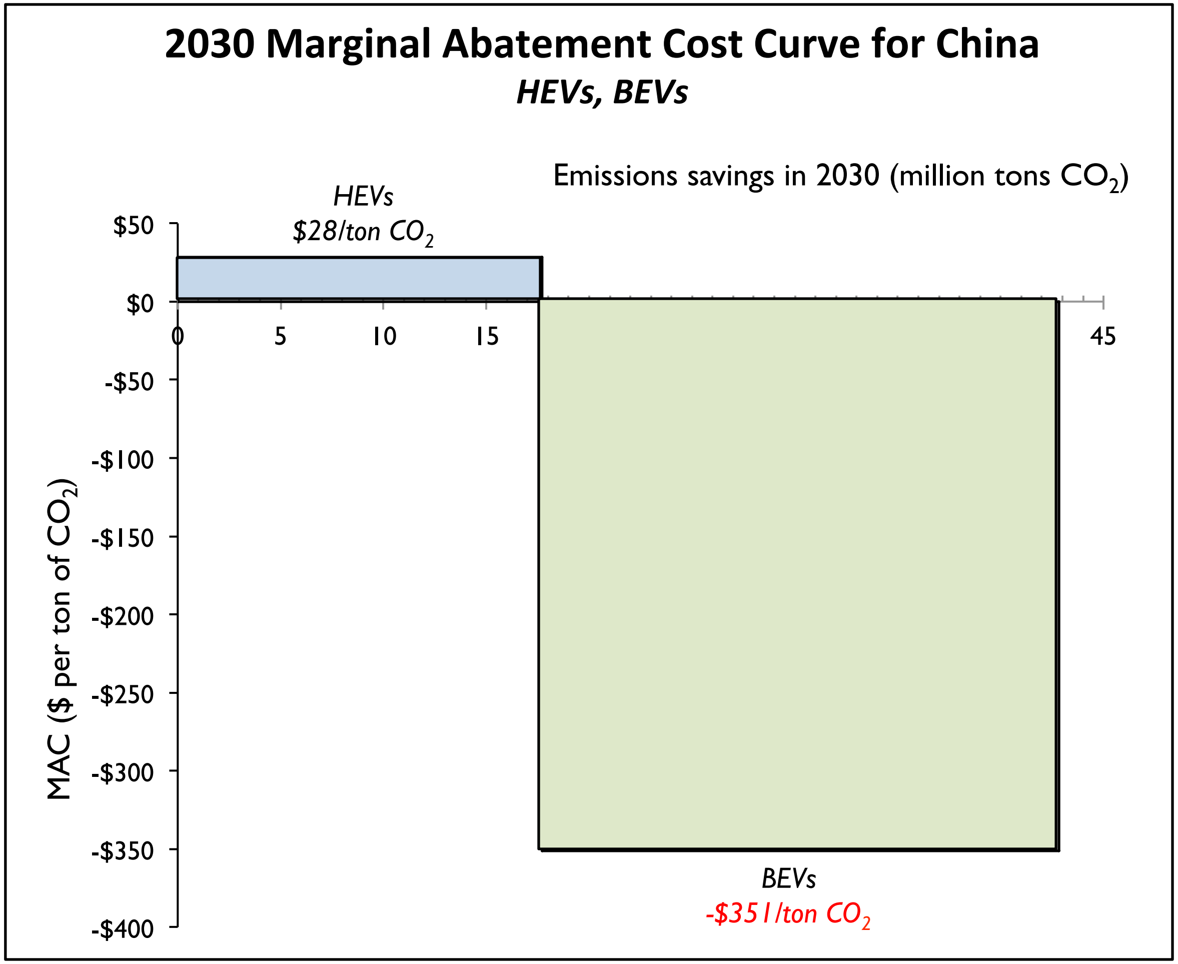
India HEV & BEV MAC Curve



- Compared to McKinsey (2009)
  - 2030 MAC for HEVs and BEVs > €100 (~ $120)/ton CO_2
  - Total abatement potential = 6 Mt CO_2e

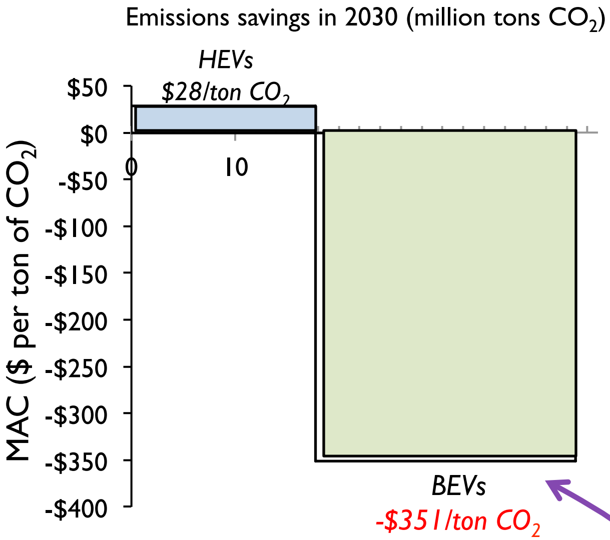
McKinsey (2009). Environmental and Energy Sustainability: An Approach for India. http://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/Sustainability/cost%20curve%20PDFs/Environmental_Energy_Sustainability.ashx

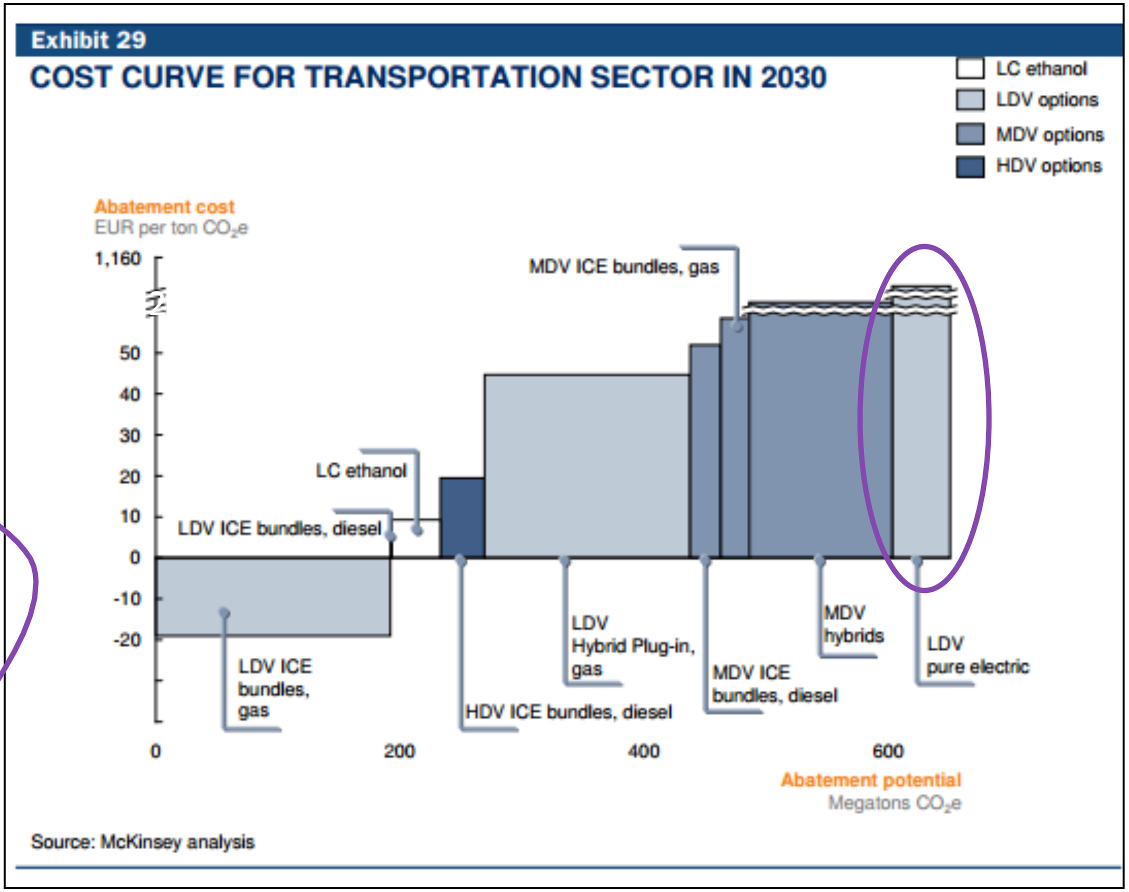
China HEV & BEV MAC Curve



China MAC Curve – Compared to McKinsey

2030 Marginal Abatement Cost Curve for China
HEVs, BEVs



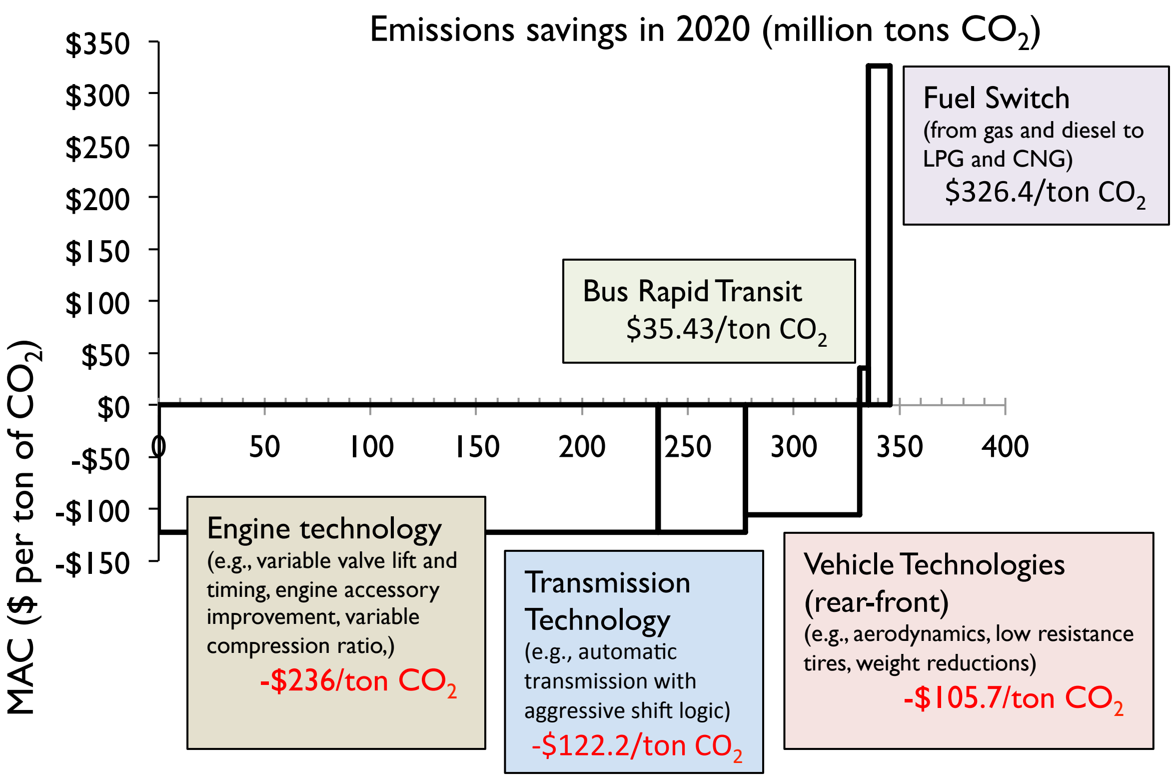


Our study shows that LDV pure electric can have negative MAC in 2030.

McKinsey (2009). China's Green Revolution: Prioritizing Technologies to Achieve Energy and Environmental Sustainability. file:///C:/Users/mwitt/Downloads/china_green_revolution%20(1).pdf

China – compared to other carbon saving measures

2020 MAC Curve, Other Transport Measures in China

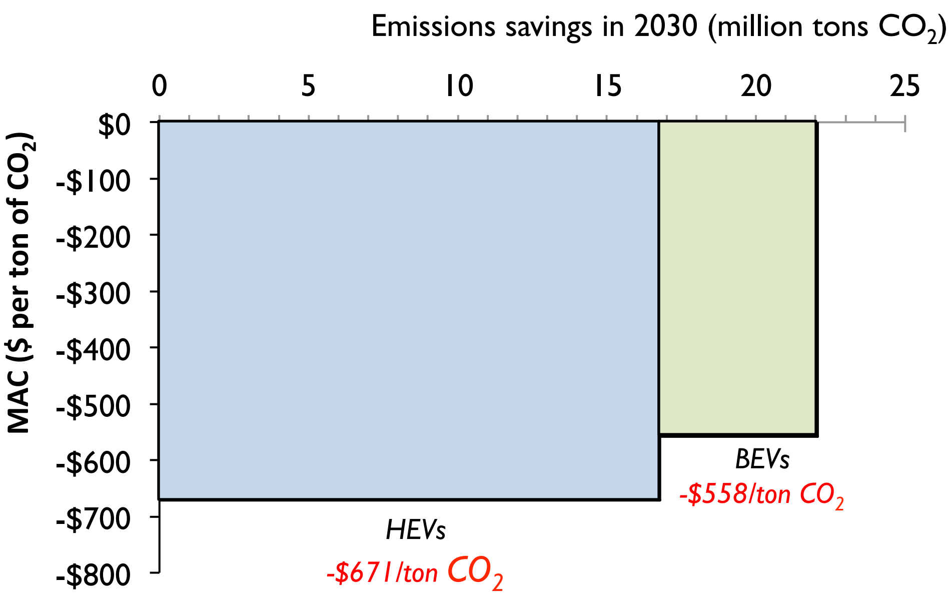


Our calculated MAC for BEVs (-$351/ton CO_2) indicates that these vehicles could be prioritized with (or even before) all measures considered in this study. Also, carbon mitigation potential for BEVs & HEVs is larger than BRT or fuel switching as found here.

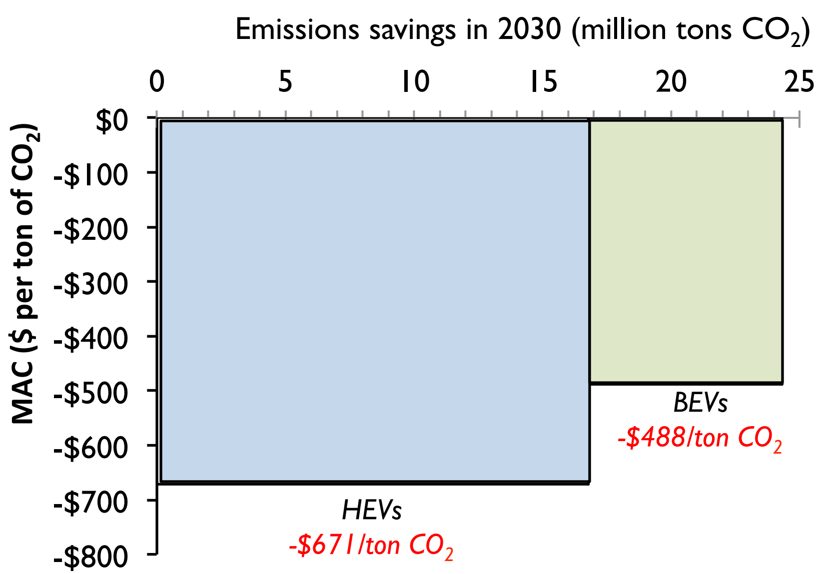
Wang, C., Cai, W., Lu, X., & Chen, J. (2007). CO_2 mitigation scenarios in China's road transport sector. *Energy Conversion and Management*, *48*(7), 2110-2118.

India – 25% cleaner grid, MACC curve

Original Estimate



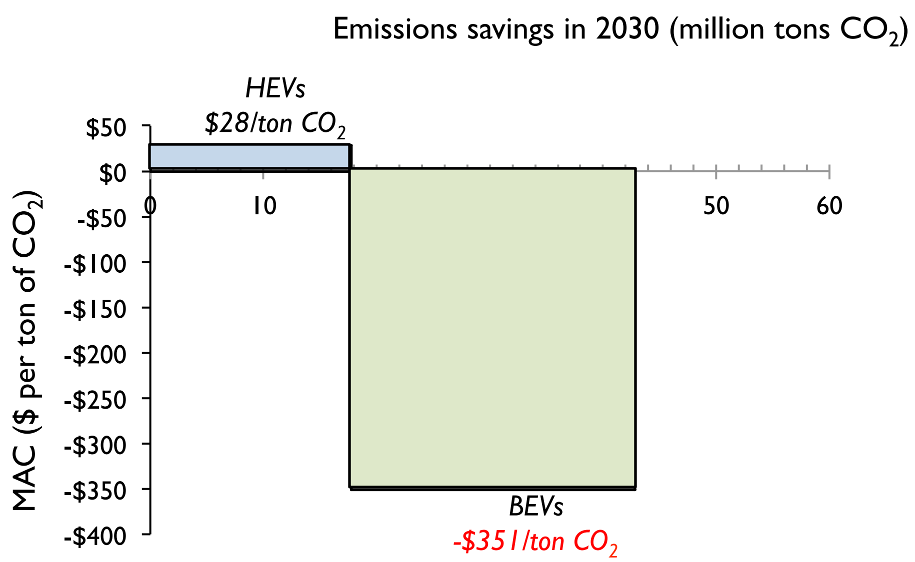
25% "Cleaner" Grid



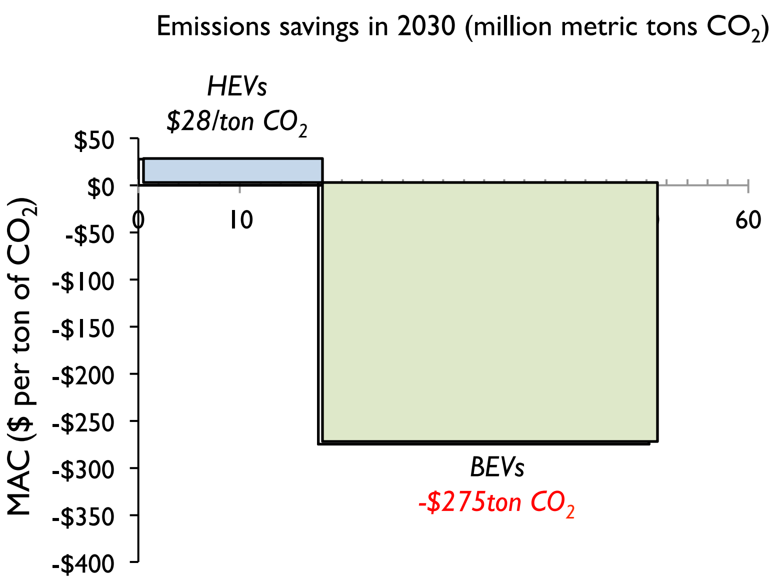
With a 25% cleaner grid, India's BEV MAC moves closer to zero and CO_2 abatement potential increases.

China – 25% cleaner grid, MAC curve

Original Estimate



25% "Cleaner" Grid



Similar to our observation with India, a 25% cleaner grid moves MAC values move closer to zero. CO_2 abatement increases as g CO_2/kWh decrease.

Policy Implications of the Results

- HEVs are a “no-regret” climate mitigation option in India and very low cost in China
- BEVs are a “no-regret” climate mitigation option in both countries in 2030
- BEVs benefit the climate even in the current coal-intensive grid but they would contribute a lot more in a cleaner grid

HEVs and BEVs are better for the climate in real-world use in China and India

Part 2

How do we increase EV adoption in India and China?

Many policies will be necessary.

Investment in Public Charging Infrastructure will be critical

EV Charging Station Infrastructure Planning – New Delhi

(Collaborator: Schatz Energy Research Center, Humboldt State University)

- Objective
  - Develop a model that can be used by anyone to optimally rollout EVSE with increasing EV penetration
  - Apply the model to New Delhi to assist India's EV Mission
- Methodology
  - Agent-based model capable of resolving the behavior of individual EV drivers based on real mobility behavior in the region
  - Site EVSE to serve all EV drivers in a region at least cost

Plug-In Electric Vehicle Infrastructure (PEVI) Model

(Collaborator: Schatz Energy Research Center, Humboldt State University)

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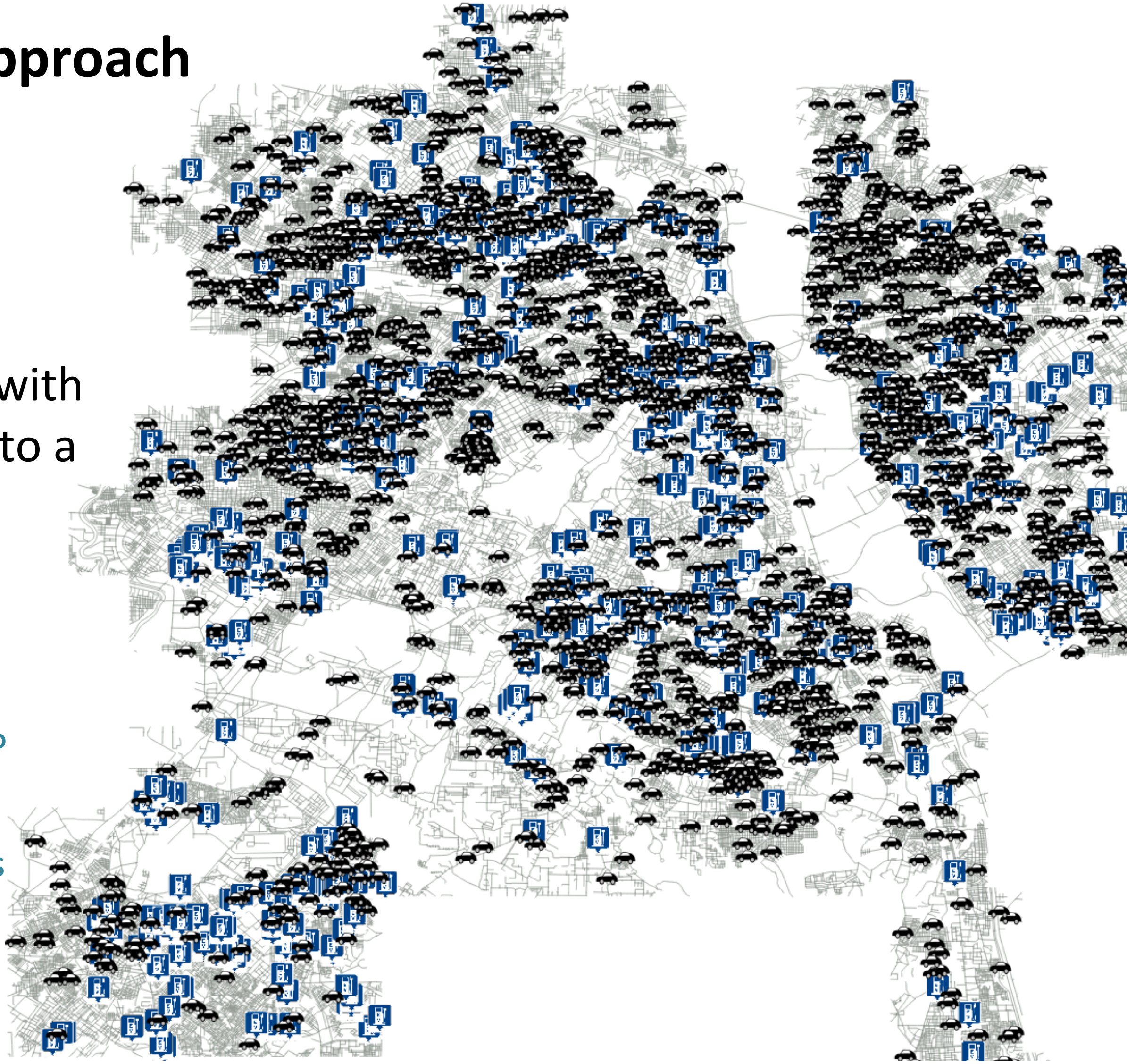
Agent-Based Modeling Approach

- Create virtual environment
  - Road network
  - Charging Infrastructure
- Create agents that interact with the environment according to a set of rules
  - EV Drivers
- Observe what happens
  - Can they complete their trips?
  - Are they on time?
  - When and where are chargers used?



A Sample New Delhi Simulation

(Collaborator: Schatz Energy Research Center, Humboldt State University)

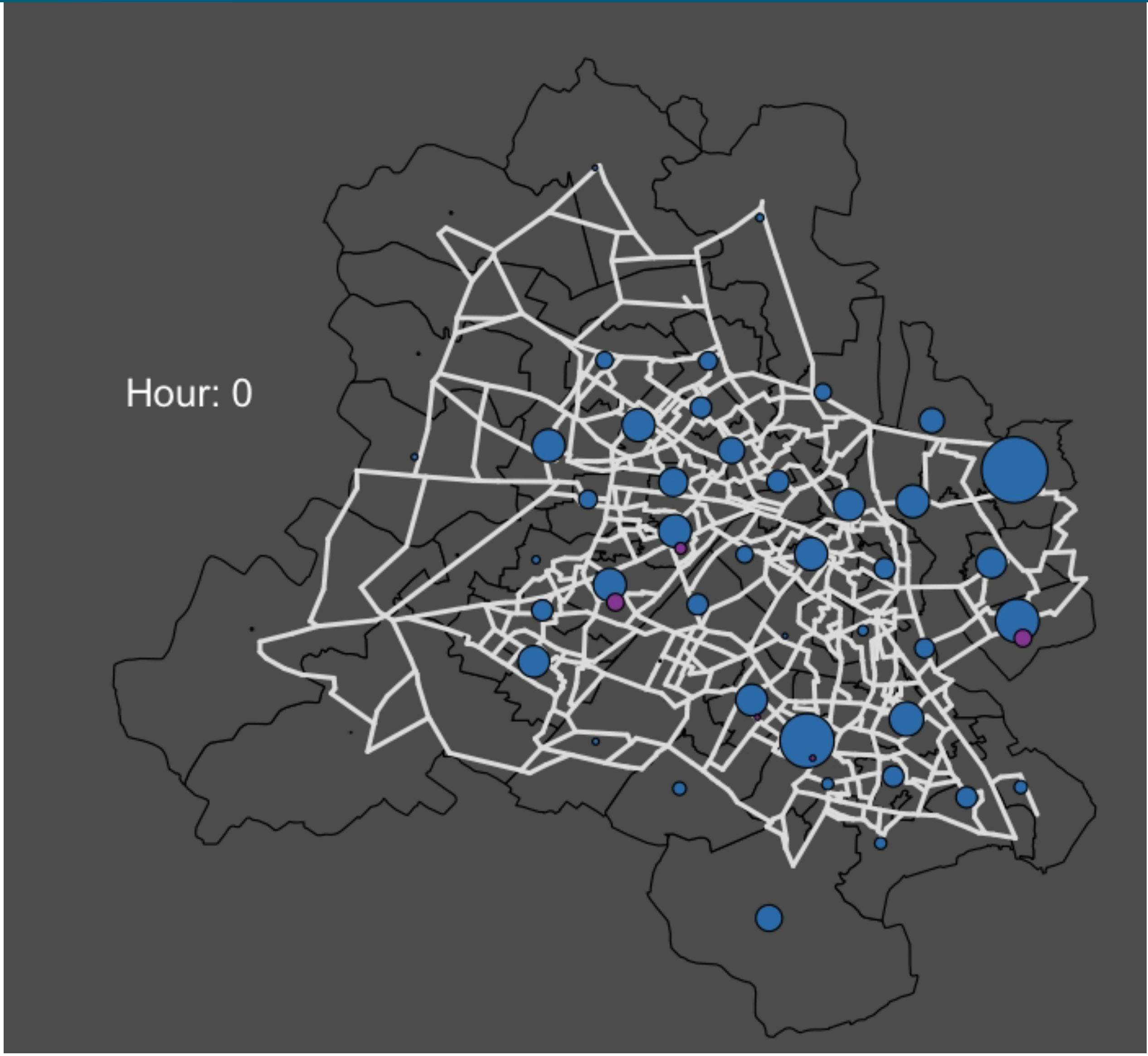
Example Simulation

Charging Events

- Residential
- Level 1
- Level 2
- Level 3

Driver Inconvenience

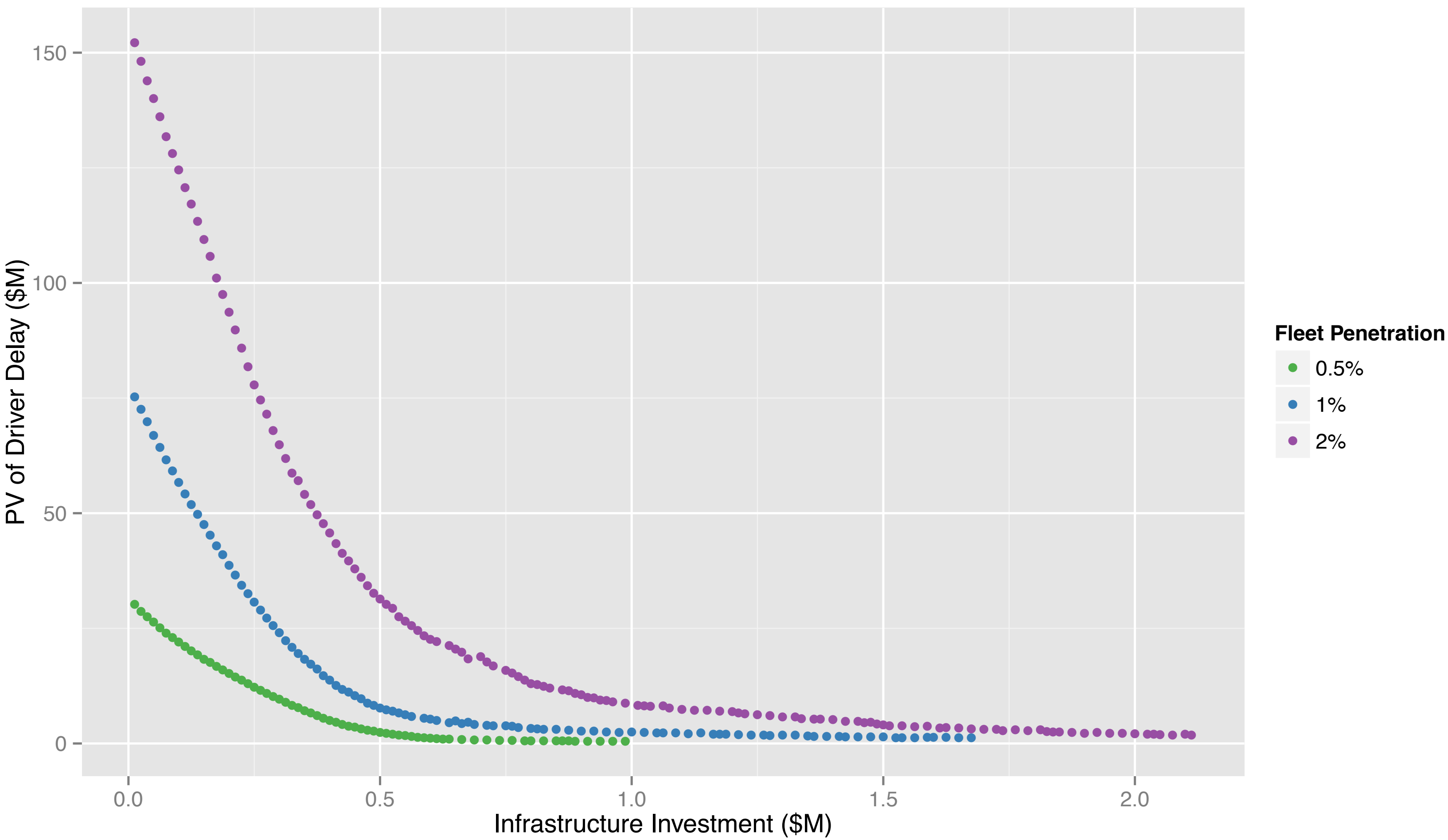
- Delayed
- Stranded



Optimization Convergence

(Collaborator: Schatz Energy Research Center, Humboldt State University)

Results for Base Case



New Delhi EVSE Layout – Base Case

(Collaborator: Schatz Energy Research Center, Humboldt State University)

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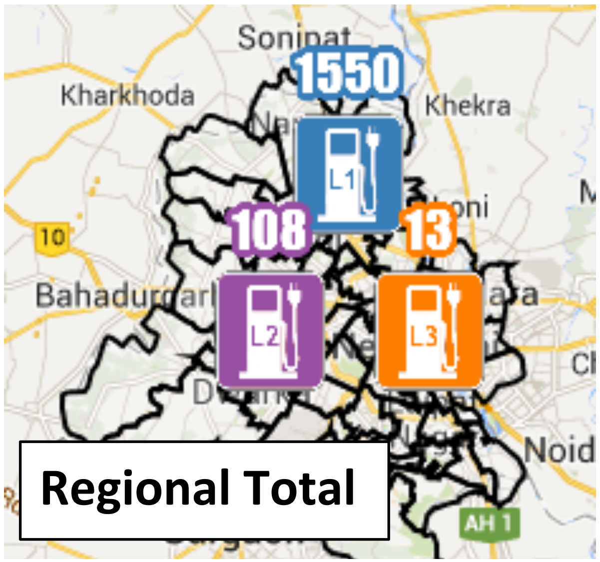
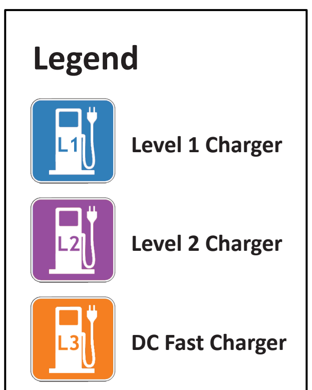
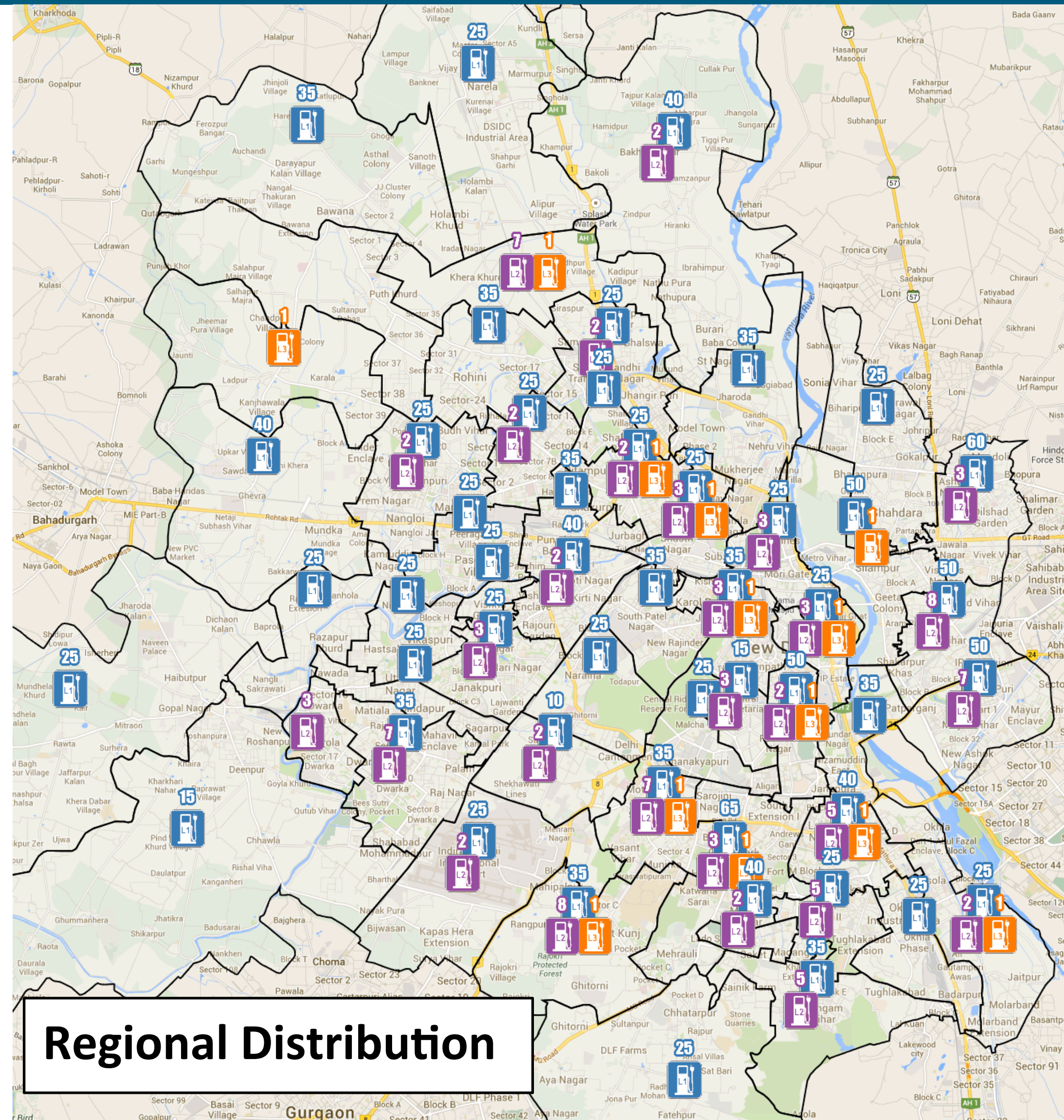
Results: Base Scenario
1% Fleet Penetration



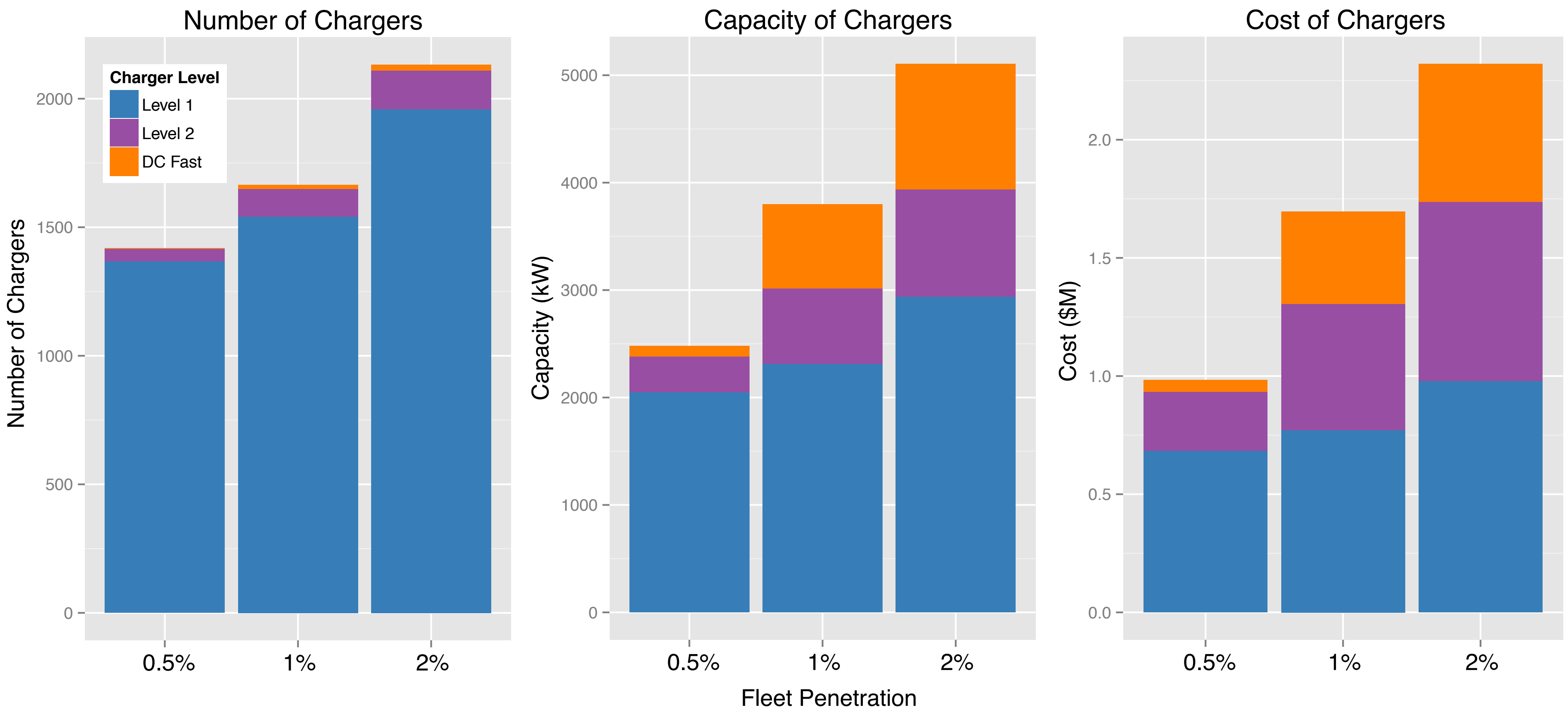




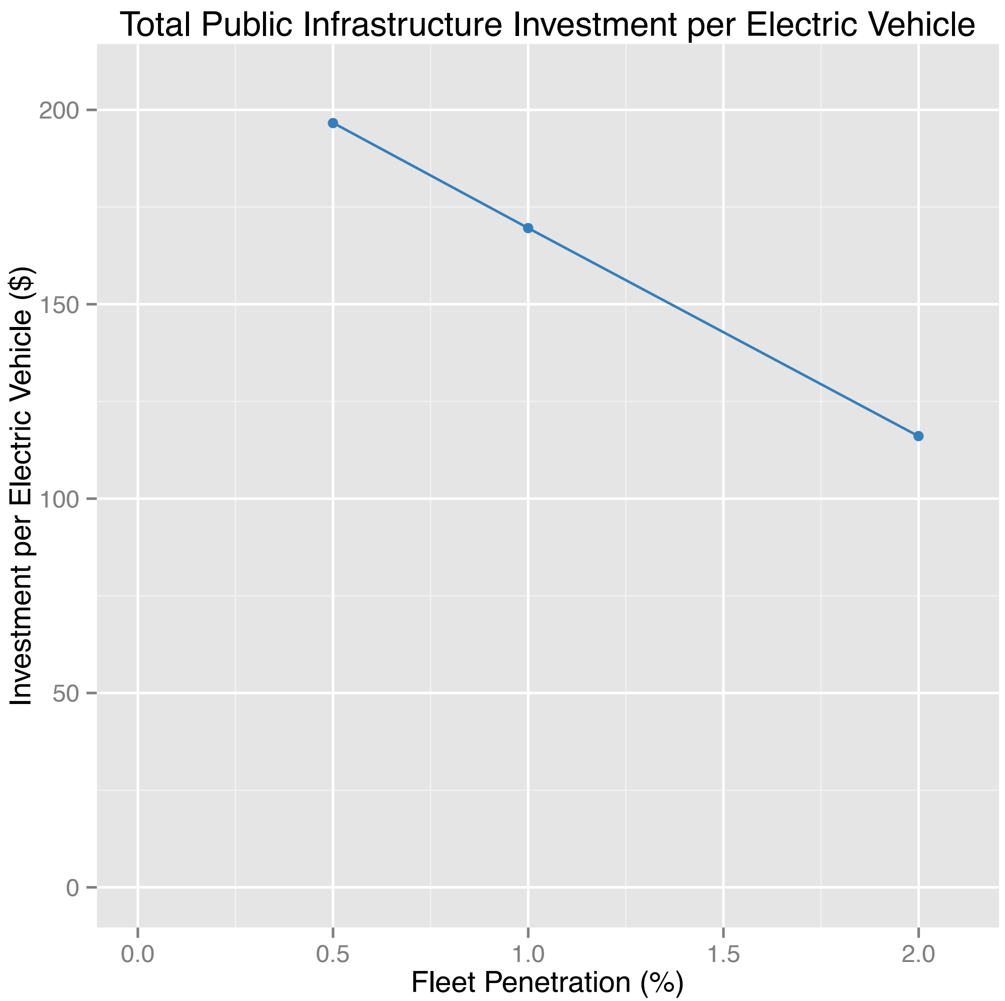
New Delhi EVSE – Base Case

(Collaborator: Schatz Energy Research Center, Humboldt State University)

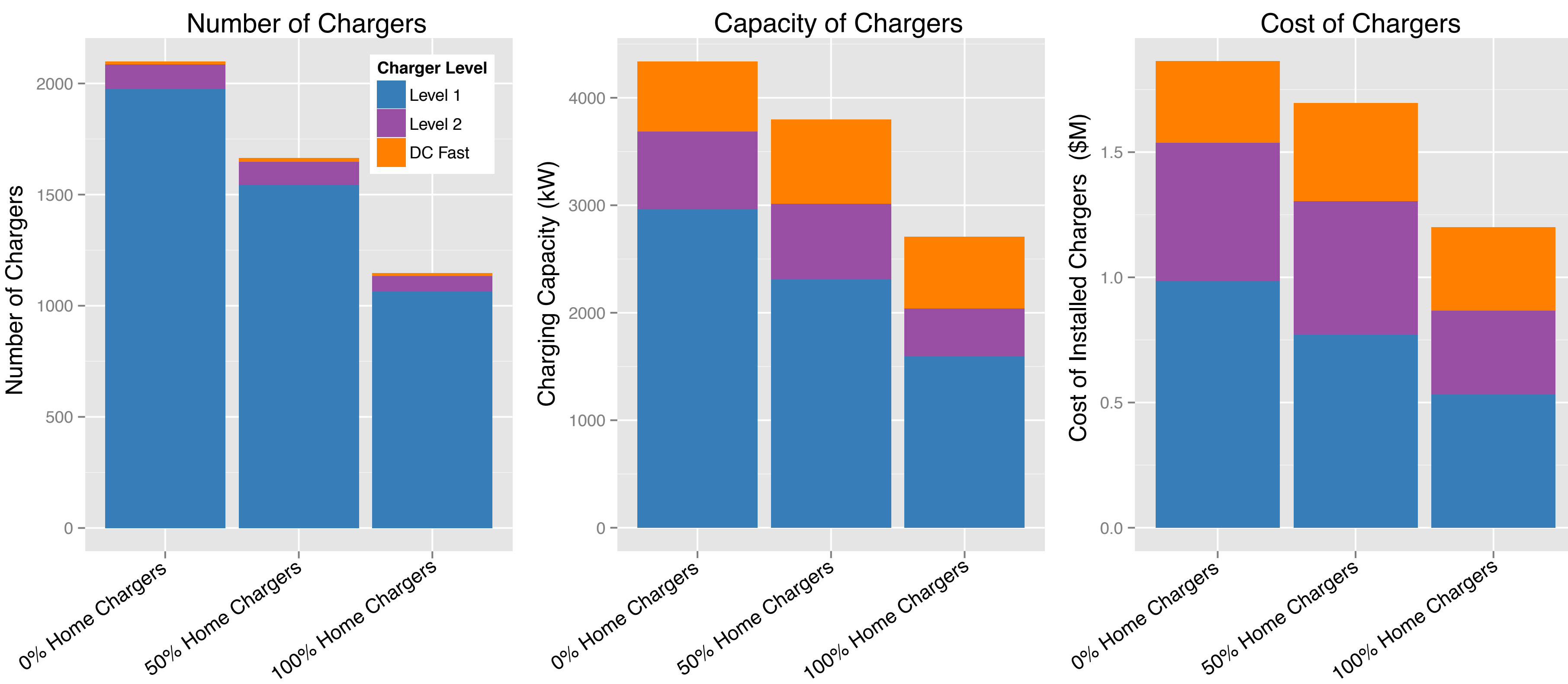
Number, Capacity and Cost of Chargers



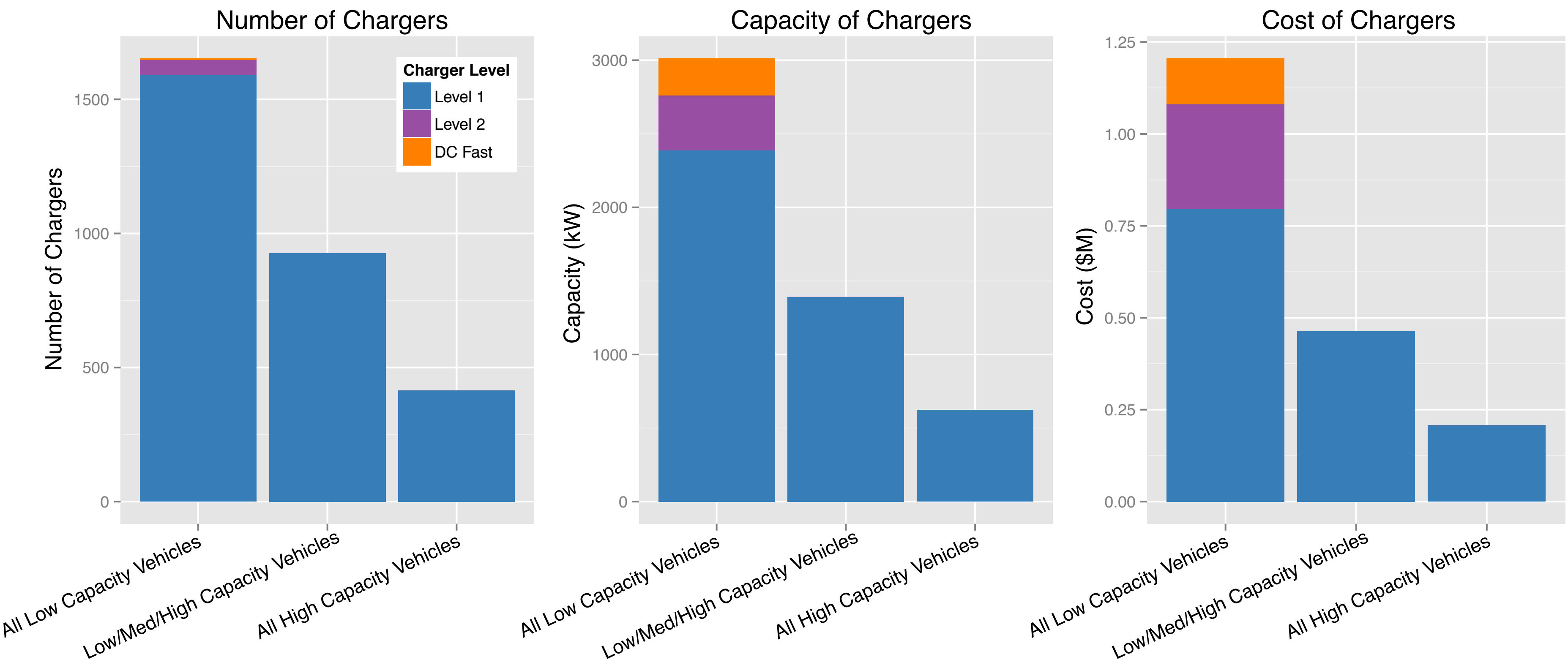
EVSE Cost per Vehicle



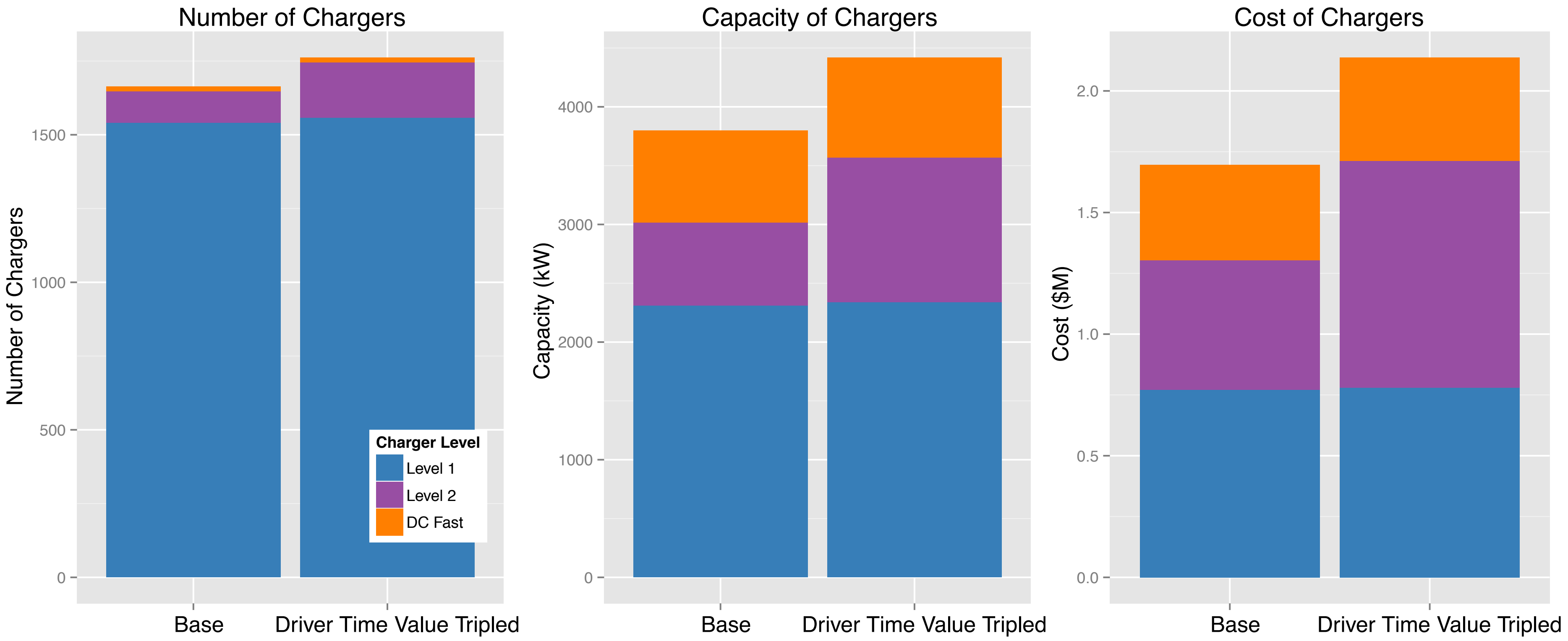
Impact of Access to Charging at Home



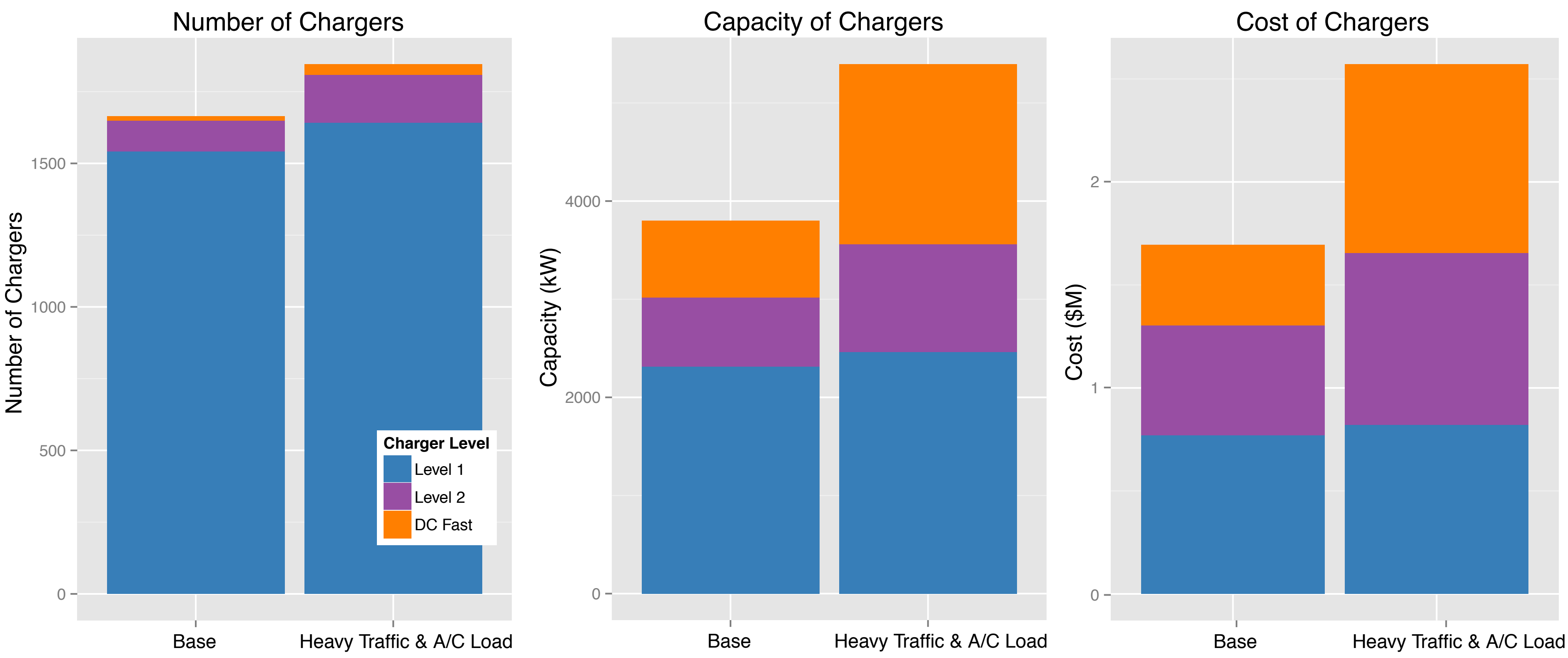
Impact of Vehicle Class



Impact of Value on Driver Time



Impact of Congestion and A/C Load



Conclusion

- Excellent Public EV Charging service can be provided at a cost of ~$170 per EV for 1% penetration in New Delhi
  - Low daily trip ranges imply that Level 1 chargers are mostly sufficient
  - There is little need for DC Fast Chargers and no need for Battery Swapping stations
  - Even high range anxiety does not change these results much

Backup Slides

How do these compare to California?

DRAFT

Analysis of Measures to Meet the Requirements of California's Assembly Bill 32

Precourt Institute for Energy Efficiency, Stanford University

Precourt Institute for Energy Efficiency

Discussion Draft September 27, 2008

Principal Investigators:

Jim Sweeney
John Weyant

3.3. Transportation sector programs

Table 8. Summary estimates for transportation

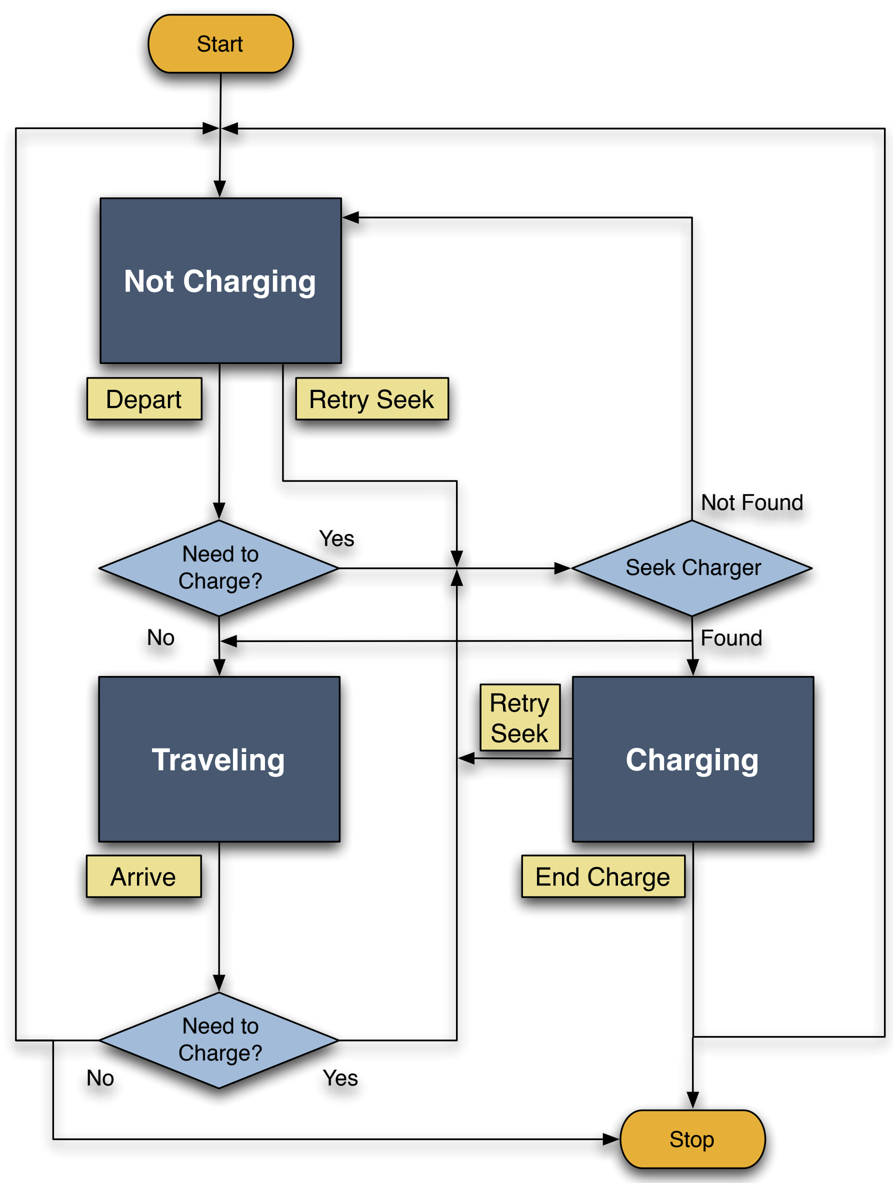
Measure	Emission Reduction ($MMTCO_2e$)	Costs (\$/tonne CO_2e)
Light duty fuel economy: 2007 Federal Energy Bill	19.6	-\$89
Light duty fuel economy: AB 1493 (Pavley)	13.7	\$35
Medium/heavy duty fuel economy	1.25	-\$175
Ethanol	6.8	\$90
Biodiesel	0.8	\$23
Light duty plug-in hybrids	6.0	\$62
Medium/heavy truck hybridization	0.5	\$68
Shore Electrification	0.55	\$56
Fuel Efficient Replacement Tires	1.34	-\$264
Diesel Anti Idling	1.46	-\$336

PEVI – Current Model Assumptions

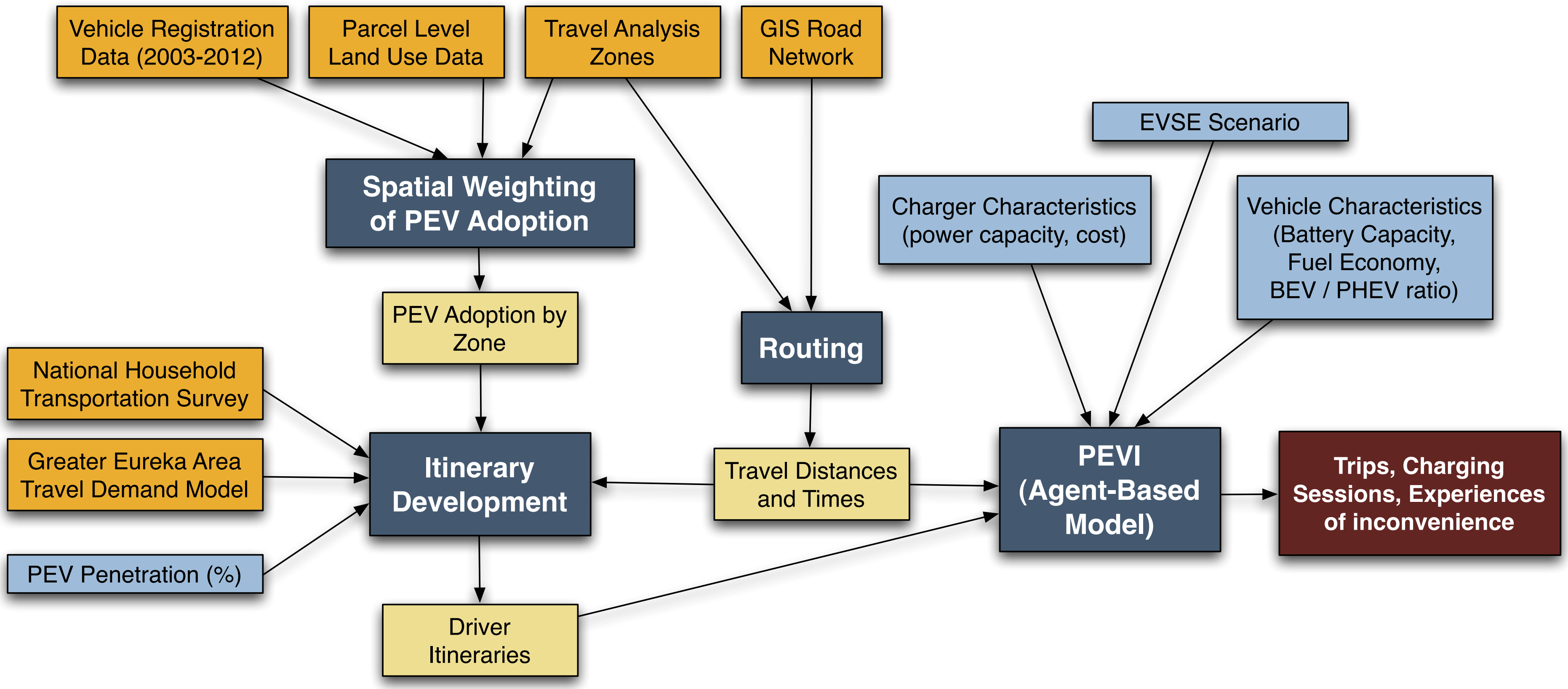
- Drivers do:
  - Attempt all of their daily trips
  - Include a factor of safety in their range estimations (10%)
  - Have a home and a charger at home
  - Charge if they need it and sometimes if they don't (randomly with probability increasing as SOC decreases)
  - Include neighboring and en-route zones in their list of candidate charging sites, but only if desperate for charge (1 hour threshold)
  - Choose the charging option that minimizes their cost
- Drivers do not:
  - Attempt unreasonable trips in a BEV (they are assigned a PHEV instead)
  - Block EVSE when the vehicle reaches a full SOC

PEVI – Current Model Characteristics

- Drivers are modeled as a finite state machine with three states:
  - Not charging
  - Charging
  - Traveling
- Transitions between the states are referred to as "events" (yellow boxes)
- Most events involve decisions (diamonds) that dictate which state is entered next
- Events are scheduled ahead of time by the drivers themselves as they enter a state



PEVI – Data Flows



PEVI – Optimizing Infrastructure

- Begin with current infrastructure
- Test impact on driver inconvenience (e.g. % drivers with delay > 3 hours) of placing level 1, 2 or level 3 charger in every possible location
- Place next charge in location and of type that minimizes the marginal cost of reducing inconvenience
- Continue until inconvenience is unchanged by placement of another charger

New Delhi EVSE

(Collaborator: Schatz Energy Research Center, Humboldt State University)

Delays and Strandings